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Aortofemoral Transfer Function: A Method to Determine the Instantaneous Aortic Valve Gradient in Aortic Valve Stenosis

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Objectives. This study was performed to evaluate the use of synthesized ascending aorta pressure, calculated from femoral artery pressure using an aortofemoral transfer function, in the assessment of aortic valve stenosis.

Background. Measurement of an accurate aortic valve gradient in patients with aortic stenosis often requires simultaneous recordings of ascending aorta and left ventricular pressures. The use of femoral artery pressure is considered to be a poor substitute for ascending aorta pressure. However, the aortic pressure wave can be calculated from the femoral artery pressure if the aortofemoral transfer function has been determined.

Method. Femoral artery pressure from the side arm of an introducer sheath and ascending aorta pressure are recorded simultaneously and the data stored in a personal computer. An aortofemoral transfer function is determined from the ratio of the Fourier components of aortic and femoral pressures. Left ventricular and femoral artery pressures are then recorded. Using the previously determined transfer function, the simultaneous ascending aorta pressure is calculated from the femoral pressure.

Results. Ascending aorta pressure waveforms estimated from femoral artery pressure closely resembled the simultaneously recorded ascending aorta pressure. Mean aortic valve gradients calculated from the synthesized aortic pressure correlated well with the gradient measured from direct recordings of aortic pressure ($r = 0.98$). There was also a good relation between valve areas ($r = 0.93$) and valve resistances ($r = 0.98$) calculated using the two methods.

Conclusions. Using current computer technology, accurate aortic valve gradients can be rapidly calculated using femoral artery pressure as a substitute for ascending aorta pressure. This technique will reduce the need and risks of multiple catheters to determine aortic valve gradients.

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Measurement of an accurate pressure gradient across a stenotic aortic valve is essential to determine the severity of the valvular obstruction. Often this pressure gradient is measured from an approximation of the difference in systolic pressures when the catheter is pulled back from the left ventricle to the aorta. Although a reasonable estimate of the pressure gradient can usually be obtained by this method, it cannot be used when the heart rate is irregular or when there is a large beat to beat variation of pressure. To determine a pressure gradient with precision requires placement of catheters in both the left ventricle and ascending aorta and simultaneous recording of high fidelity pressures. This is only possible if two catheters are introduced retrogradely from two peripheral arteries or into the left ventricle by the transseptal route. Both methods require additional instrumentation with its associated risks.

Simultaneous femoral artery and left ventricular pressure recordings are often used as a method to estimate the aortic valve gradient. However, serious limitations reduce the accuracy of the femoral artery pressure as a substitute for ascending aorta pressure (1). Although the transmission time delay between the ascending aorta and femoral artery can be corrected, the aligned femoral and left ventricular pressures often underestimate the pressure gradient (2) because the femoral artery pressure contour differs substantially from that of the central aortic pressure.

The present report describes a one-catheter technique that can be used to measure the instantaneous aortic valve pressure gradient. The method determines the transfer function of aortofemoral transmission to calculate a more precise estimate of ascending aorta pressure from recordings of femoral artery pressure. Using readily available computer technology, this method is applicable in the routine catheterization laboratory and is of greatest value in patients with a small aortic gradient, irregular heart rate or widely varying aortic pressures.

Methods

Subjects. The study group comprised 15 patients with a clinical and echocardiographically confirmed diagnosis of aortic valve stenosis undergoing routine elective cardiac

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Table 1. Clinical and Hemodynamic Data in the 15 Study Patients

Pt No.	Age (yr)/ Gender	HR (beats/min)	CO (liters/min)	Pressures (mm Hg) AoS	AoD	AoM	LVS	SEP (s)	SVR (dynes·s·cm^{-5})
1	76/F	70	4.8	168	54	82	201	0.34	900
2	69/F	53	5.1	124	54	63	145	0.24	847
3	66/M	88	4.6	132	80	98	184	0.25	1,391
4	68/M	62	4.1	125	59	81	199	0.33	1,151
5	72/F	103	4.5	107	58	65	115	0.2	1,031
6	68/M	73	4.6	109	50	60	141	0.3	870
7	61/F	74	5.5	153	60	94	200	0.32	873
8	72/M	81	4.7	134	75	94	169	0.27	1,277
9	63/F	98	5.1	131	74	97	222	0.26	1,161
10	69/M	78	3.2	122	82	95	178	0.28	2,050
11	69/F	83	4.8	147	90	92	241	0.29	1,500
12	61/F	60	3.5	155	54	87	155	0.22	1,234
13	67/M	59	6.3	129	61	70	171	0.29	775
14	69/F	70	4.8	149	61	82	193	0.26	1,017
15	68/M	84	4.5	121	78	85	132	0.2	1,387
Mean	68	76	5	134	66	83	176	0.27	1,164
SD	4	14	0.7	17	12	12	33	0.04	321

AoD = aortic diastolic pressure; AoM = aortic mean pressure; AoS = aortic systolic pressure; CO = cardiac output; HR = heart rate; LVS = left ventricular systolic pressure; Pt = patient; SEP = systolic ejection period; SVR = systemic vascular resistance.

catheterization. The demographics and baseline hemodynamic variables are shown in Table 1. Of the 15 patients, 7 were male, with an average age of 68 ± 4 years. Heart rate varied between 53 and 103 (76 ± 14) beats/min. Three of the 15 patients had chronic atrial fibrillation.

Hemodynamic study. Left heart catheterization was performed through the femoral artery with an 8.5F sheath (Daig) for vascular access. Size 7F or 8F pigtail or A2 multipurpose catheters (Cordis Corp.) were used for aortic and left ventricular catheterization. Pressures were measured using standard fluid-filled transducers (Gould PD23) after ensuring that all air had been removed from the system. Femoral artery pressure was measured from the side arm of the vascular access sheath. In 10 patients the left ventricle was entered retrogradely across the aortic valve; in the other 5 patients left ventricular access was by the transseptal route. Simultaneous pressures were recorded from the femoral artery and ascending aorta, femoral artery and left ventricle and, in the five patients with left ventricular catheters introduced by the transseptal route, from the left ventricle and ascending aorta.

The frequency response of the catheter systems was verified using a standard step test. For the vascular sheath side arm recordings, the undamped natural frequency was 50 Hz, with a relative damping of 0.22. This results in a 4% distortion and a 0.09-radian phase lag at 10 Hz. For the 7F catheter used in the aortic and left ventricular recordings, the undamped natural frequency was 54 Hz, with a relative damping of 0.25. The distortion at 10 Hz is 3% and the phase lag 0.10 radian.

Recording equipment. The pressures and electrocardiogram were amplified and recorded using a PPG Electronics for Medicine Midas recorder. Pressures were recorded at a paper speed of 50 cm/s for subsequent manual planimetry. The analog output of the Midas recorder was connected to a Data Translation analog to digital converter (DT 2801) within a 486-based personal computer. The analog data were digitized at a frequency of 100 Hz/channel, and 12 s of data was stored on the computer hard disk for analysis.

Recording and analysis of the data were performed using custom-written software. As a result, calculations of the valve hemodynamic variables were available within seconds of completing the recording.

Data analysis. The estimation of ascending aorta pressure from femoral artery pressure was calculated using the transfer function H(z), which relates the femoral artery (FA) to the ascending aorta (Ao) pressure wave,

$$t[FA(z)] = H(z) \cdot t[Ao(z)],$$

where t represents the z transforms of the pressure signals and z the harmonic number of the transform. In the present analysis, 1,024-point fast Fourier transforms of 10.24 s of simultaneously recorded aortic and femoral artery pressure signals were used to calculate the transfer function H(z). The transfer function is calculated as the ratio t[FA(z)/t[Ao(z)] for each harmonic by division of the two complex numbers. Because the transfer function has both an amplitude and a phase, it relates not only the magnitude of the two pressure waves, but also their temporal relation.

The effect of signal noise results in a false transfer function, especially at higher frequencies. In the present study, the transfer function was calculated only for individual harmonics when the harmonic components of the moduli of femoral artery pressure were greater than the average

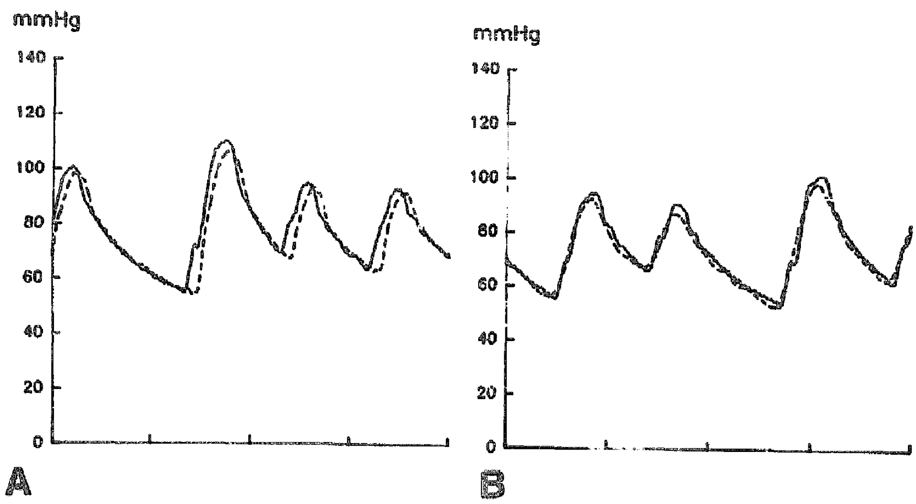

Figure 1. Patient with atrial fibrillation. **A,** Simultaneously recorded ascending aorta (solid line) and femoral artery (dashed line) pressures used for calculation of the transfer function. **B,** Recorded ascending aorta pressure (solid line) and synthesized aortic pressure (dashed line) from simultaneous femoral artery pressure and the transfer function determined from the previous recording of the two pressures.

noise level of 0.5 mm Hg. The average upper frequency limit of the transfer function was 7.5 ± 0.7 Hz.

The transfer function is then used to calculate an estimate of the ascending aorta pressure wave from the femoral artery pressure recorded simultaneously with left ventricular pressure. The 10.24 s of femoral artery pressure recording is transformed into a 1,024 Fourier series using a fast Fourier transform. The frequency domain estimate of ascending aorta pressure is calculated as $t[Ao(z)] = t[FA(z)]/H(z)$ by complex division for each harmonic z up to the cutoff frequency limit of the transfer function, as described earlier. Above this frequency, Ao(z) is set at 0.

The estimate of ascending aortic pressure is converted from a frequency domain spectrum to a time series by inverse fast Fourier transformation of Ao(z). Before the inverse fast Fourier transform of Ao(z), the frequency spectrum Ao(z) is multiplied by a digital filter (Dolph Chebyshev) that tapers the modulus Ao(z) toward 0 as the cutoff frequency imposed by the transfer function is reached (3). This is necessary to diminish the presence of artifactual oscillations in the synthesized aortic pressure wave that result from high frequency truncation of the discrete frequency spectrum Ao(z).

The systolic aortic valve pressure gradient was calculated as the difference between the digitized left ventricular and synthesized aortic pressures averaged over the period of ejection. The left ventricular ejection time was measured as the time interval between the two crossover points of ventricular and aortic pressures. Aortic valve area (AVA) was calculated using the standard Gorlin formula for the aortic valve (4):

$$AVA = \frac{CO/(HR \cdot SEP)}{44.3 \cdot (Grad)^{1/2}}$$

where CO = cardiac output (liters/min); HR = heart rate (beats/min); SEP = systolic ejection period (s); and Grad = mean aortic valve systolic pressure gradient (mm Hg).

Aortic valve resistance (dynes·s·cm^{-5}) was calculated as follows:

$$\frac{Grad \cdot HR \cdot SEP}{CO} \times 1.33.$$

Planimetry of pressure signals. The computer-generated aortic valve gradient using the femoral artery pressure and aortofemoral transfer function was compared with the aortic valve gradient measured manually from hard copy recordings using a Summagraphics digitizing tablet interfaced to a personal computer. The manual analysis of the pressure gradients was performed independently and without knowledge of the computer-derived gradient.

In the five patients with simultaneously recorded left ventricular and ascending aorta pressures, the aortic valve pressure gradient was determined by manual planimetry of the recorded pressures. In the remaining patients, the pressure gradient was determined from aortic and left ventricular pressures recorded consecutively. The aortic pressure recording traced on thin paper was superimposed as accurately as possible on the left ventricular pressure recording, and the mean gradient was calculated by planimetry of the pressure traces.

Statistical analysis. The results are expressed as the mean value ± SD of each measurement. The aortic valve gradient, valve area and valve resistance determined by the transfer function method were compared with measurements determined by the standard manual planimetric method using regression analysis.

Results

Ascending aorta pressure synthesized from femoral artery pressure using the aortofemoral transfer function determined from a previous recording and compared with the simultaneously recorded aortic pressure is shown in Figure 1 (right). Despite the irregular rhythm, the pressure contour of

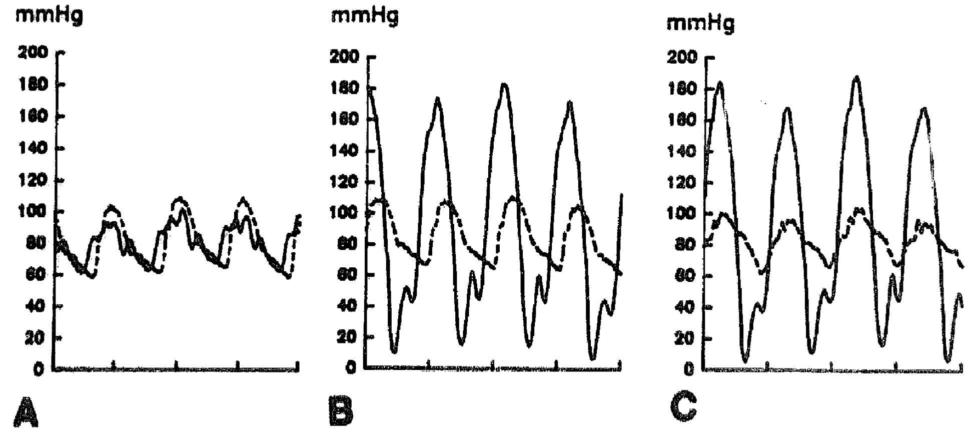

Figure 2. Patient with severe aortic stenosis and varying pressures due to pulsus alternans. A, Aortic (solid line) and femoral artery (dashed line) pressures. B, Left ventricular (solid line) and femoral artery (dashed line) pressures. C, Left ventricular (solid line) and synthesized aortic (dashed line) pressures.

the synthesized waveform closely resembles the true aortic pressure wave. Recordings of aortic, femoral, left ventricular and synthesized aortic pressure for patients with sinus rhythm and atrial fibrillation are shown in Figures 2 to 4. Figure 2 shows the recordings from a patient with severe aortic stenosis and a regular rhythm. Use of a realigned femoral artery recording would have underestimated the gradient in this case. Figures 3 and 4 show the value of the technique in patients with a small aortic valve gradient and an irregular heart rhythm. In these patients, only simultaneous recordings of aortic and left ventricular pressures would otherwise allow an accurate calculation of the aortic valve gradient.

The calculated valve gradients, valve areas and valve resistances are shown in Table 2, and the relation between the two methods is illustrated in Figure 5. The mean gradient calculated by the transfer function method appeared to slightly overestimate the mean gradient determined by manual planimetry, with the correlation function having a slope of 0.89 and an offset of 5.6. The r value was 0.98. The valve area and valve resistance determined by the two methods were also closely related. For valve area of slope 0.80 and intercept 0.06, r = 0.93. For valve resistance of slope 0.88 and intercept 23, r = 0.98.

Movement of the catheter within the sheath may theoretically alter the higher frequency content of the femoral artery pressure waveform because of inhomogeneities of the sheath valve and changes of the position of the catheter within the sheath. In five patients the femoral artery pressure was recorded on two occasions before and after reintroduction of the same catheter into the femoral artery sheath. There was no significant difference in frequency content from 0 to 8 Hz of the two femoral artery pressure waveforms. This indicates that catheter movement is unlikely to change the femoral artery pressure wave contour over the frequency range used in the transfer function analysis.

Discussion

Femoral artery pressure is a poor substitute for ascending aorta pressure in the measurement of an aortic valve gradient (2). In the present study, differences between the pressure contours of aortic and femoral pressures are apparent (Fig. 1 to 4), and the use of the uncorrected femoral artery pressure could result in a significant error in the calculation of the aortic valve gradient. Such an error is particularly important in patients with severe aortic stenosis and a small gradient due to low cardiac output.

The present transfer function method of estimating aortic pressure resulted in transvalvular gradients that were very similar to those measured by conventional methods. Differences between the methods may be the result of limitations in the accuracy of the conventional measurement of valve gradients. When the pressure gradient was determined from

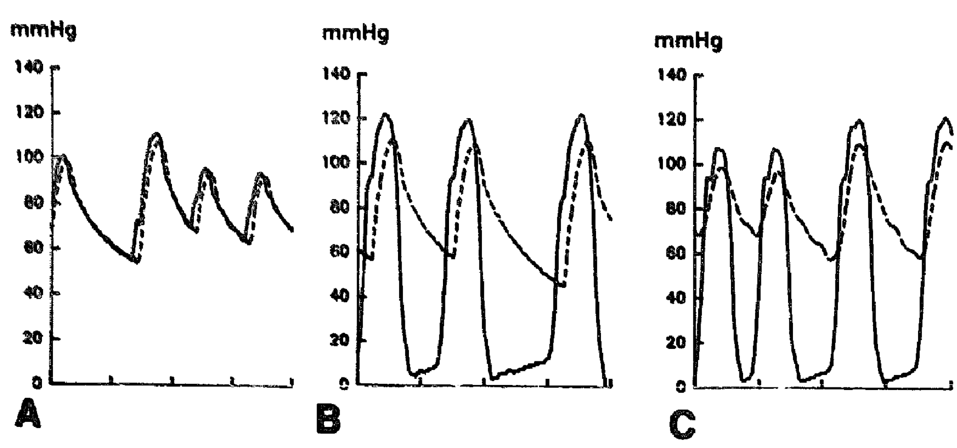

Figure 3. Patient with mild aortic stenosis and atrial fibrillation. A, Aortic (solid line) and femoral (dashed line) artery pressures. B, Left ventricular (solid line) and femoral artery (dashed line) pressures. C, Left ventricular (solid line) and synthesized aortic (dashed line) pressures.

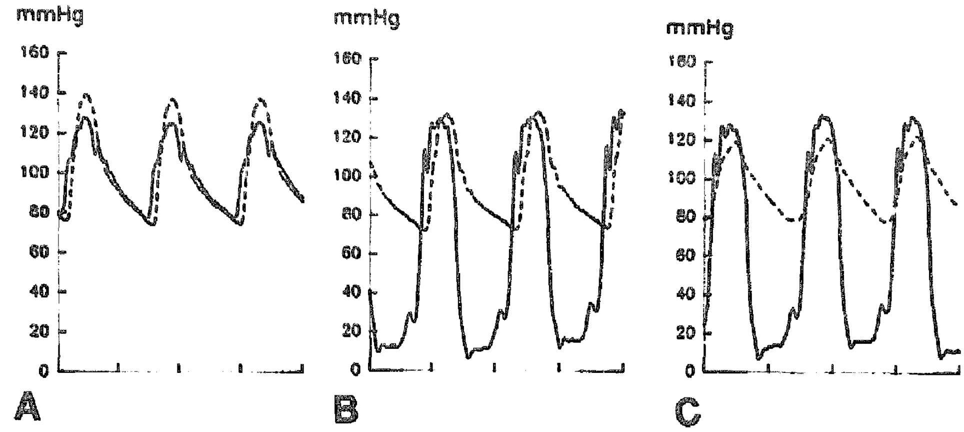

Figure 4. Patient with mild aortic stenosis. A, Aortic (solid line) and femoral (dashed line) artery pressures. B, Left ventricular (solid line) and femoral artery (dashed line) pressures. C, Left ventricular (solid line) and synthesized aortic (dashed line) pressures.

simultaneous recordings of aortic and left ventricular pressures, there was a closer relation to the transfer function–derived gradient than when the aortic valve gradient was estimated from a pullback recording of the two pressures. Such a difference is probably due to difficulties in the accurate superimposition of serially recorded aortic and left ventricular pressures for manual planimetry. Although this study suggested that the transfer function method slightly overestimated the aortic valve gradient, the use of a regression equation to better predict aortic valve gradient is not recommended until a larger series of simultaneously recorded left ventricular and aortic pressures have been analyzed.

Limitations of the method. The use of transfer functions assumes linearity of pressure transmission in the arterial system. Several studies tested the linearity of the arterial system and have shown that only very small errors are introduced by ignoring nonlinear components (5). O'Rourke et al. (6) recently used an averaged transfer function to predict ascending aorta pressure from noninvasive recordings of the peripheral radial artery pressure contour. Their results show that this analysis gives a close approximation of ascending aorta pressure (7) and that the transfer function in the upper limb varies little despite age, arterial pressure or body size. In contrast, the aortofemoral transfer function is highly sensitive to the presence of hypertension and atherosclerosis and to aging and has to be determined for each subject. In the present study, the transfer function was measured in each patient from recordings of ascending aorta and femoral artery pressures performed before the aortic valve was crossed.

Accurate resynthesis of an aortic wave from the femoral artery pressure using the aortofemoral transfer function is dependent on an adequate frequency content in the femoral pressure recording. A diminished frequency content could occur as a result of a mechanical obstruction in the femoral

Table 2. Comparison of Planimetry-Derived and Computer-Derived Aortic Valve Data

Pt No.	Planimetry-Derived Data: Ao Gradient (mm Hg)	Valve Area (cm^2)	Valve Resistance (dynes·s·cm^{-5})	Computer-Derived Data: Ao Valve Gradient	Ao Valve Area	Ao Valve Resistance
1	41	0.62	271	35	0.9	231
2	30	1.5	100	26	2.3	86
3	48	0.73	306	47	0.8	300
4	68	0.5	452	80	0.6	532
5	14	1.6	85	11	1.8	67
6	33	0.7	209	32	1.1	203
7	44	0.9	253	50	0.9	287
8	37	0.9	230	36	0.9	223
9	62	0.5	413	73	0.6	486
10	49	0.5	446	51	0.5	464
11	83	0.4	555	81	0.6	541
12	28	0.9	141	29	1.1	146
13	55	1.1	199	52	1.3	188
14	39	1.1	197	39	1.1	197
15	14	2.1	70	12	2.2	60
Mean	43	0.9	262	44	1.1	267
SD	18	0.5	142	21	0.5	160

Ao = aortic; Pt = patient.

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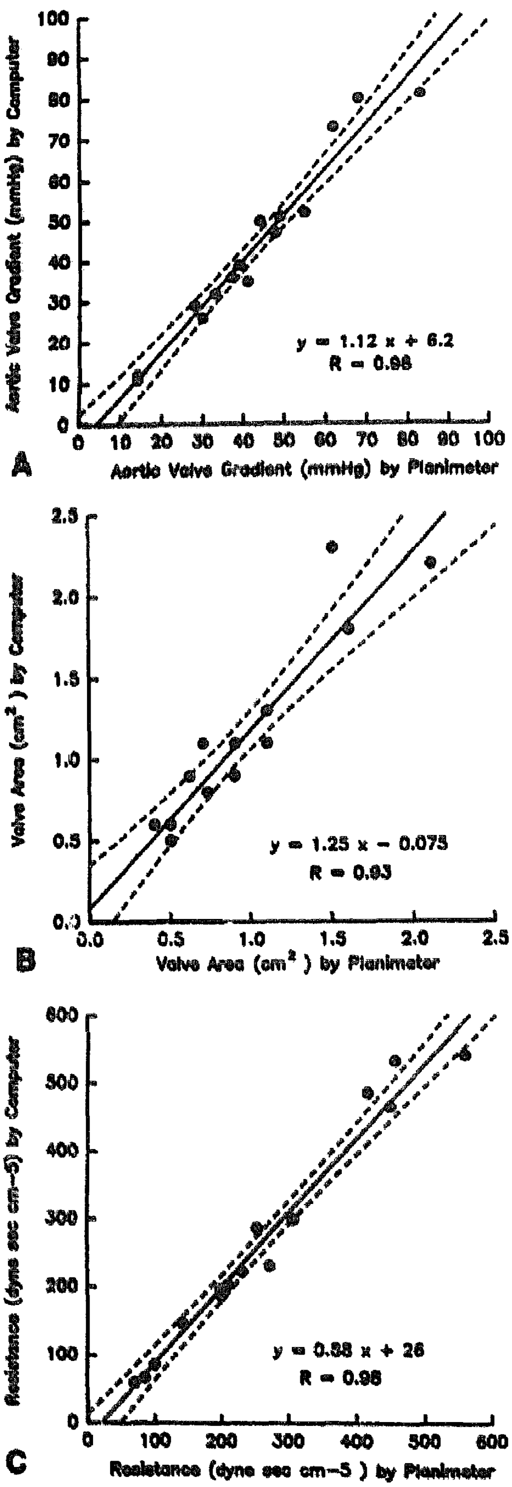

Figure 5. Regression lines and 95% confidence intervals (dashed lines) for (A) aortic valve gradient, (B) aortic valve area and (C) aortic valve resistance determined by the automated transfer function method and by manual planimetry.

sheath or a vascular stenosis. For adequate femoral pressure recordings, it is essential that the lumen of the femoral artery sheath is 1F size larger than the catheter and that the sheath lumen is frequently flushed with heparinized saline solution. The presence of a major arterial stenosis in the iliac vessels will also severely dampen the femoral artery pressure waveform and limit the predictive value of the transfer function.

Although our results show that catheter movement is unlikely to change the frequency content of the femoral artery pressure waveform, to ensure that the method is accurately calculating aortic pressure we routinely perform a second recording of aortic and femoral artery pressures. The transfer function calculated from the first aortic and femoral pressure recording is then applied to the second femoral artery recording, and the calculated aortic pressure is compared with the simultaneously recorded aortic pressure.

Conclusions. The use of the transfer function to synthesize ascending aortic pressure allows more precise determination of aortic valve gradient than can be made from femoral artery pressure recording alone. In patients with small aortic valve gradients and atrial fibrillation, this method reduces the need to introduce two arterial catheters to simultaneously record left ventricular and aortic pressures. The system used in this study can calculate accurate measurements of aortic valve resistance and area within seconds of completion of the recording and is applicable for use in the routine catheterization laboratory.

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